31. A Revised Stochastic Sampled Data Model for Eye Tracking Movements*

L. R. Young, J. D. Forster, and N. Van Houtte
Massachusetts Institute of Technology

Our sampled data model is revised by changing the pursuit system to be continuous and proportional to target rate. Transient responses of the model are shown to agree in detail with observed classes of eye movements. Target-synchronized and non-synchronized sampler control logic are compared. Predicted latency distributions of a nonsynchronized sampler with unknown intersample time distribution are analyzed, and saccade synchronized input experiments are compared with predicted mean model responses. The results show properties of both types of sampler control logic. The assets, limitations, and extensions of the model are discussed. The sampled data model proves to be a useful tool for predicting eye response based on target movement only.

INTRODUCTION

The discrete nature of the saccadic eye movement control system has been well established (refs. 1, 2, and 3). Several types of discrete systems have been proposed to model eye tracking movements including preprogramed systems, saturating systems, digitally controlled systems, and sampled data systems. It is questionable whether the minute differences between these systems allow differentiation among them in defining, from present research, the exact nature of the eye movement control system. For example, any system at all could be equated to a preprogramed system that yields the observed output to each input. Further, a target-synchronized sampled data system need only choose its stochastic distribution of synchronization times appropriately to model exactly observed latency distributions. The sampled data model, however, is a simple, analyzable, deterministic means of predicting eye movement based on target movement only.

The purpose of this paper, then, is to present our sampled data model, which has been revised in view of recent experiments by several researchers, and to discuss its assets and limitations. Further, the synchronization of sampling instants relative to target motion will be investigated as a possible source of the variability of response observed in following identical experimental stimuli.

*This research was supported by NASA Grant NsG-577.

FURTHER STUDIES

Young (ref. 3) proposed a sampled data model for eye tracking movements in which both the saccadic and pursuit eye movement control system were sampled functions of retinal error. In analyzing model outputs he made the simplifying assumption that the sampler was synchronized to the onset of target motion if the eye had made no saccadic movement in the last 0.2 second. Since Young proposed this model, several studies have shed further light on the eye movement control system.

Rashbass (ref. 4) has shown that the pursuit eye movement control system is independent of the saccadic eye movement control system and sensitive only to target rate rather than target position. Rashbass demonstrated that certain classes of step-ramp target movements generally elicit no saccadic response. Robinson (ref. 2) used these no-saccade step-ramps to show that the pursuit eye movement control system could make changes temporally spaced by the same time as target rate changes for spacings as low as 150, 100, and 75 msec. Robinson also performed variable feedback experiments around only the pursuit system, by eliminating saccadic eye movements from the feedback signal. He observed only smooth continuous changes in pursuit eye movement response. Robinson therefore concluded that while a sampled data system gave good results for the saccadic eye movement control system, the pursuit eye movement control system was continuous rather than sampled. Vossius (ref. 5) proposed a structure of such a system, including a sampled data saccadic eye movement control system and a continuous pursuit eye movement control system, but made no attempt to define operational functions.

Zuber (ref. 6) performed two experiments in attempting to define the nature of sampling in the eye movement control system. His ramp-step-ramp experiment showed that some information available only after the step occurred was used in determining the size of saccadic response to the step. The predictive nature of this result is compatible with nonsynchronized sampling and with sampling synchronized a constant or stochastic time after the step. The size of the sampled error depends on the time from the step to the next sampling instant. Zuber's step with variable blank period (no target displayed) experiment showed only random variation of error. This result is incompatible with sampling synchronized a constant time after a target step but is compatible with stochastic target-synchronized sampling and with nonsynchronized sampling.

Beeler (ref. 1) and Wheeless (ref. 7) each noted pulse input results that do not agree completely with Young's model. Beeler noted longer latencies in returning pulses than in continuing pulses for short pulse widths. Wheeless found that in cases where a pulse input elicited no response, the pulse had not gone unnoticed, but in fact delayed response to an immediately following step input in the opposite direction by an average of 40 msec. This result suggests a finite pulse width, with positive and negative portions during some samples canceling each other, forcing a wait for the second sample.

Several other related studies have been carried out, examining the first sampled data model. Jury and Pavlidis (ref. 8) noted that Young's model erroneously predicted pursuit movement to small steps. Johnson (ref. 9) suggested a similar system with two switches. Meiry (ref. 10) and Sugie (ref. 11) presented systems that included the sampled data model as a visual subsystem. Dallos and Jones (ref. 12) and Michael (ref. 13) studied the effects of target movement predictability on the eye movement control system transfer function. Lässig (ref. 14) showed that the transfer behavior of a nonlinear system depends on the incoming signal and that differences in eye tracking transfer behavior with predictable and nonpredictable signals do not necessarily indicate learning properties but may reflect the influence of nonlinearities. Fender presented an excellent layman's review of the area. Milhorn (ref. 15), Milsum (ref. 16), and Jones and Milsum (ref. 17) have reviewed sampled

data modeling of the eye movement control system as an example of modeling physiological systems. Fuchs (ref. 18) performed similar experiments to Young's, using monkeys, and Saslow (ref. 19) investigated target position predictability effects on step input latency.

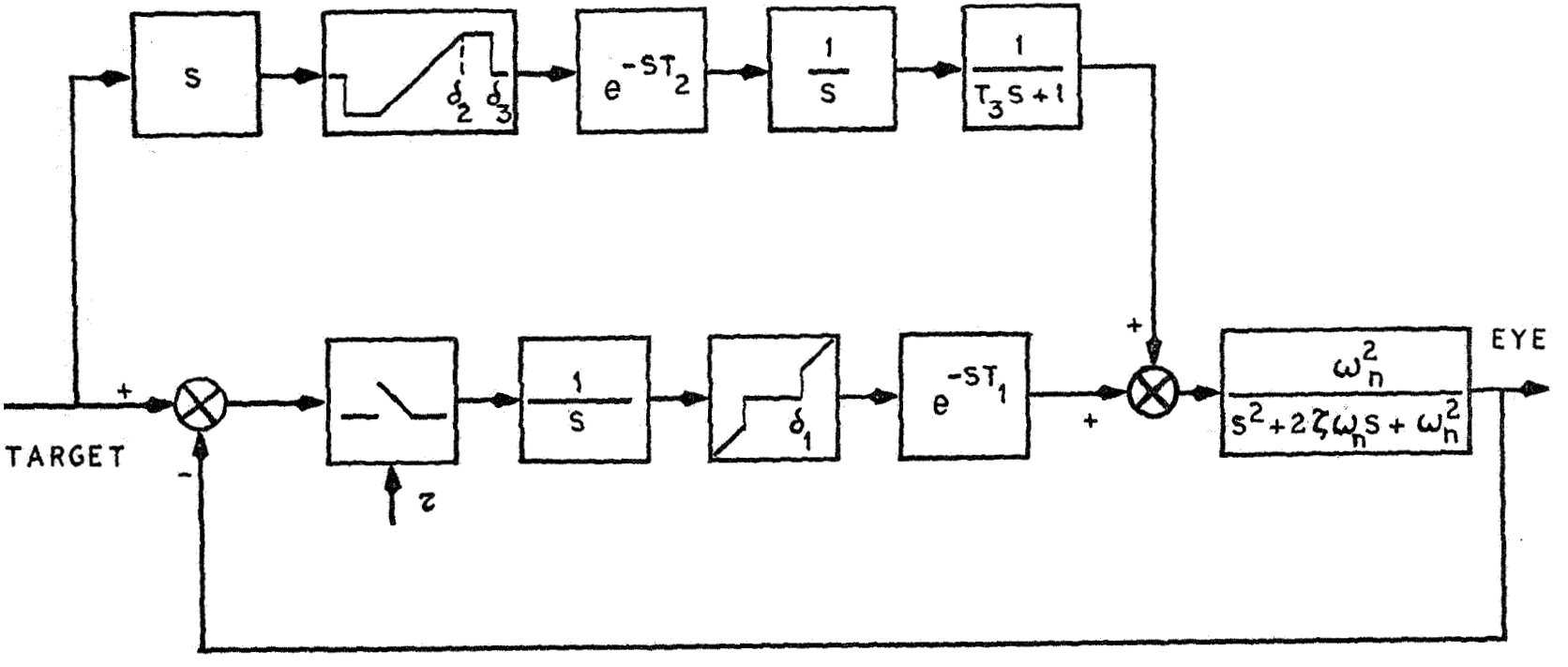
THE REVISED MODEL

Our current model for nonpredictive eye tracking movements is presented in figure 1. The saccadic eye movement control system of Young's original model has only been altered by reducing the delay, retaining the excellent saccadic response characteristics of that model. The pursuit eye movement control system has been made a continuous, open-loop function of target rate. In the pursuit eye movement control system, target position is continuously differentiated, then passed through a nonlinearity that exhibits both saturation and cutoff characteristics. The signal is then integrated to form position commands and delayed before being introduced to the eye dynamics. Eye position is only fed back to the saccadic eye movement control system, so that all position errors, even those due to the pursuit system, are corrected by saccades. The open loop system avoids limit cycles that arise in a continuous closed loop system with delay. This system agrees with Rashbass's findings that the pursuit and saccadic systems are independent and the pursuit system is target-rate sensitive. The system also agrees with Robinson's finding that the pursuit system was continuous and with experimental results that show saccades correcting position errors due to lagging pursuit movements. We now feel that Westheimer's (ref. 20) observation in 1954 that pursuit velocity changes discretely is misleading, since these abrupt changes only seem to appear when facilitated by a saccade.

To predict observed inaccuracies in saccadic eye movements, the slope of the major line in the foveal dead zone nonlinearity must be allowed to be a stochastic variable. A slope less than 1 would produce an undershoot inaccuracy and a slope greater than 1 would produce an overshoot inaccuracy. Similarly, the variability in pursuit movement observed by Robinson may be modeled by stochastically varying the slope of the pursuit nonlinearity. Such a variable slope could account for the ramp responses that Robinson shows have eye velocity exceeding the target velocity, as described in conjunction with figure 2. The definition of these stochastic processes and the possibility of further dynamics in the pursuit system are topics for further research.

Both stochastic target synchronized and nonsynchronized sampler control laws are compatible with Zuber's results and should be further investigated in an attempt to reveal the nature of sampling in the eye movement control system. Target-synchronized sampler control implies that target movement is continuously monitored, and when movement is observed, a stochastic delay elapses before a sample can be affected. The sample is then followed by a constant processing delay before the eye movement response. This theory receives some support from the hypothesis of Robinson (ref. 2) that different mechanisms control fixation and movement in the eye. The fixation system could be continuous with the ability to trigger a sampled data eye movement system. If target synchronized sampling is to match observed pulse input results, a further requirement, that of a minimum time between samples of approximately 200 msec, must be imposed. This target-synchronized system needs only specify stochastic delays before the sample, to be distributed exactly as observed latency minus the constant delay, in order to match exactly step latency distributions of observed eye movement.

Nonsynchronized sampler control logic implies that samples always continue to be taken whether retinal error has occurred or not, and the occurrence of a target movement does not alter the time of the next occurrence of a sample. If this control logic occurs in the eye movement control system, then latency distributions must be explainable on the



SACCADIC DELAY	$T_1 = 150$ ms	DEAD ZONE	$\delta_1 = .3$ deg	$\tau = {}^{200-}_{240}$ ms
PURSUIT DELAY	$T_2 = 134$ ms	SATURATION	$\delta_2 = 30^{deg/s}$	$\zeta = .7$
PURSUIT LAG	$T_3 = 40$ ms	CUTOFF	$\delta_3 = 100^{deg/s}$	$\omega_n = 120^{rad/s}$

Figure 1.—Eye tracking movement model.

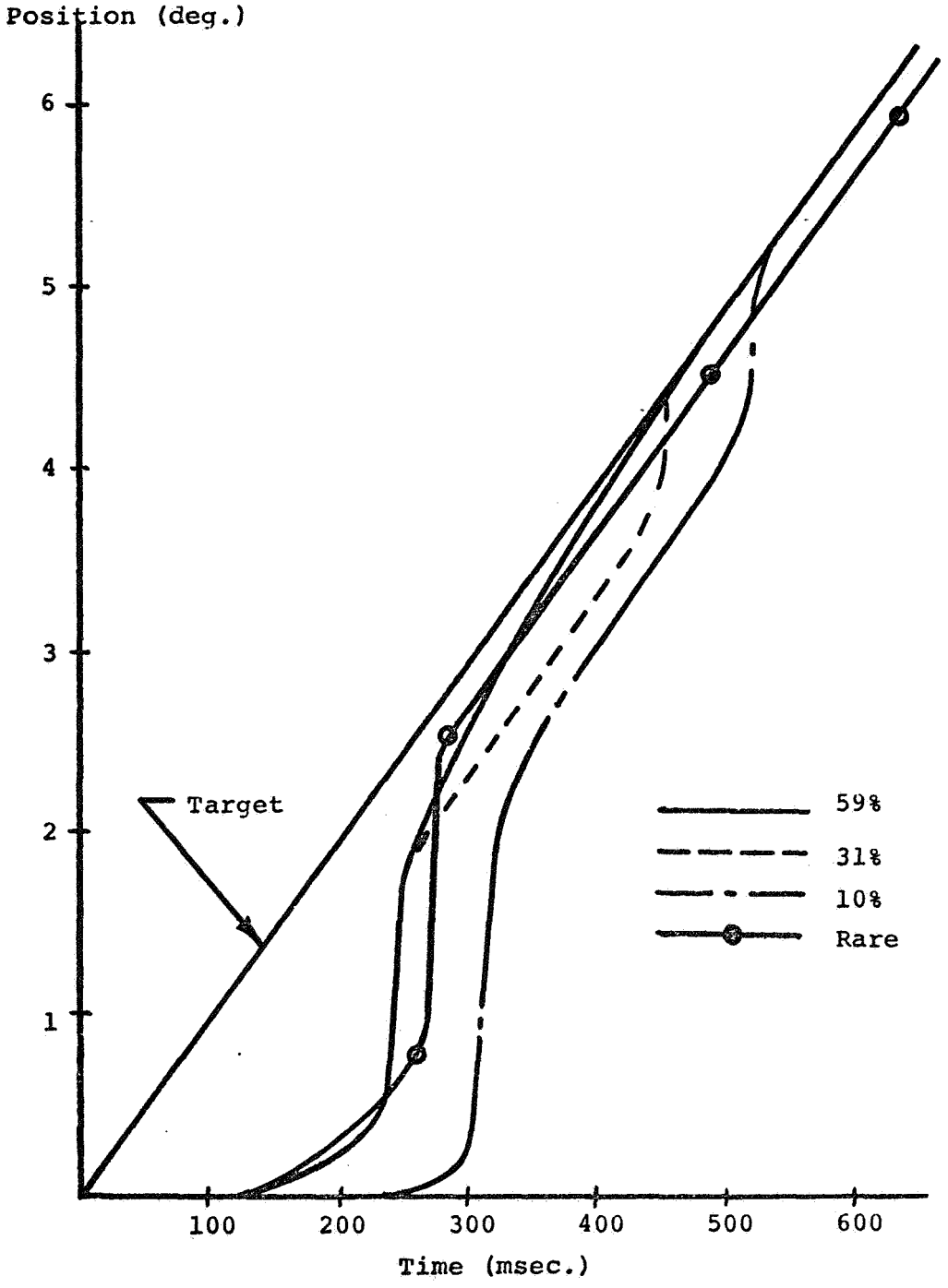


Figure 2.—Eye response to 10 deg/sec ramp stimulus (from Robinson)

basis of the frequency distribution of times between samples. Latency (L) predicted by the model is given by the sum of the time (D) from the occurrence of an input to the occurrence of a sample plus the constant delay (T_1 in fig. 1):

$$L = D + T_1$$

Since T_1 is a constant, it simply translates the distribution of D along the time axis in forming the distribution of L. The shape of the distribution of D, then, must be the same as the distribution of L which should agree with observed latency. The relation of D to the sampling interval τ in which the input occurs is the difference between τ and the time from the sample t as seen in figure 3.

$$D = \tau - t$$

From elementary probability theory, the density function of a random variable that is the difference of two other random variables may be written in terms of the density function of the other random variables as:

$$f_D(D) = \int_{-\infty}^{+\infty} f_t(\tau - D)\, f_\tau(\tau)\, d\tau$$

The lower limit of $f_t(\tau - D) f_t(t)$ is zero and the upper limit of $f_\tau(\tau)$ is τ_{max}. Therefore, the limits of integration reduce to D and τ_{max}. Since the occurrence of an input does not change the next occurrence of a sample, t may be assumed uniformly distributed over the maximum sampling interval τ_{max}.

$$f_t(t) = \begin{cases} 1/\tau_{max} & 0 < t < \tau_{max} \\ 0 & \text{otherwise} \end{cases}$$

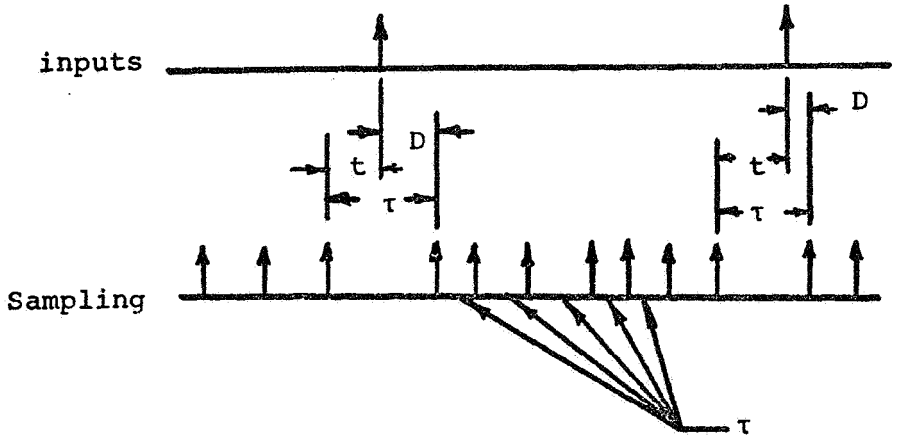


Figure 3.—Nonsynchronized sampler control logic timing.

Therefore $f_t(\tau-D)$ is constant and may be taken out of the integral. Since D is positive by definition the probability density function of D becomes

$$f_D(D) = \begin{cases} 1/\tau_{max} \int_D^{\tau_{max}} f_\tau(\tau)\, d\tau & 0 < D < \tau_{max} \\ 0 & \text{otherwise} \end{cases}$$

Since $f_\tau(\tau)$ must be positive, as D increases less and less positive area will be included in this integral. Therefore $f_D(D)$ must be strictly nonincreasing. This result has been verified by Monte Carlo simulation by Forster (ref. 21).

Clearly an $f_\tau(\tau)$ could be constructed such that $f_D(D)$ exactly fits the decreasing portion of actual latency distributions. The jump from zero to the maximum value could then be placed to make the integral over $f_D(D)$ unity. Since actual latency distributions do increase, the form of the resulting distribution would be misleading, and so this fitting process loses its meaning. Because of these increases in actual latency distributions for the first approximately 50 msec of possible latency, if nonsynchronized sampling occurs in the eye movement control system, the eye must sometimes be able to shorten the sampling interval when a target movement is observed.

TRANSIENT RESPONSE

With the model as outlined in figure 1, and using the parameters as discussed previously, a number of target-eye movement responses will be discussed.

(1) Figure 4 shows model input-output pairs for pulses, steps, ramps, step ramps, and parabolas. The time scale is superimposed on the input. The pulses indicate the sampling intervals, at a rate of five per second (τ=0.2 second). The timing of each pulse indicates the synchronization of the sample.

Figure 4(a) shows a step input of 5 degrees, with the first sample appearing 100 msec after the input. The saccadic delay of 100 msec adds further latency, such that the response begins 200 msec after the input. The same pattern appears at the return of the input. Figure 4(b) shows three sets of target pulses. Two samples occur during the first pulse, and the output is much longer than the input, returning only after 300 msec beyond the target return, due to the very last processed sample. The second pulse is sampled only once, and the output is of approximately the same duration as the input. Figure 4(b3) shows an input pulse of almost the same size as in the second example, but it has fallen between sampling instants, and leads to no response.

Figure 4(c) shows the model response to ramp inputs of 10 deg/sec. The first example shows that after a pursuit delay of 125 msec, the model is pursuing the target, but with an offset in position. The first sample occurred when the error was less than the 0.5° of threshold of the saccadic system. Following the second sample, a saccade corrects the position error and the eye is on target. At the end of this input, the output of the model exhibits the sawtooth response (ref. 20), with the error corrected after the next sampling instant. The second example shows that in the case of a step-ramp input (the step being in opposite direction of the ramp), there are two saccadic corrections of opposite sign. At the end of the input, we notice an offset error within the dead zone characteristics. The third case uses an identical input to the second one, but a shift in timing of the samples. Unlike the second one, its response does not show any saccades at all.

Figure 4(d) shows the response to a parabola of 10 deg/sec^2. Notice the continuous pursuit output, interrupted periodically by saccades, which reduce the accumulating position error.

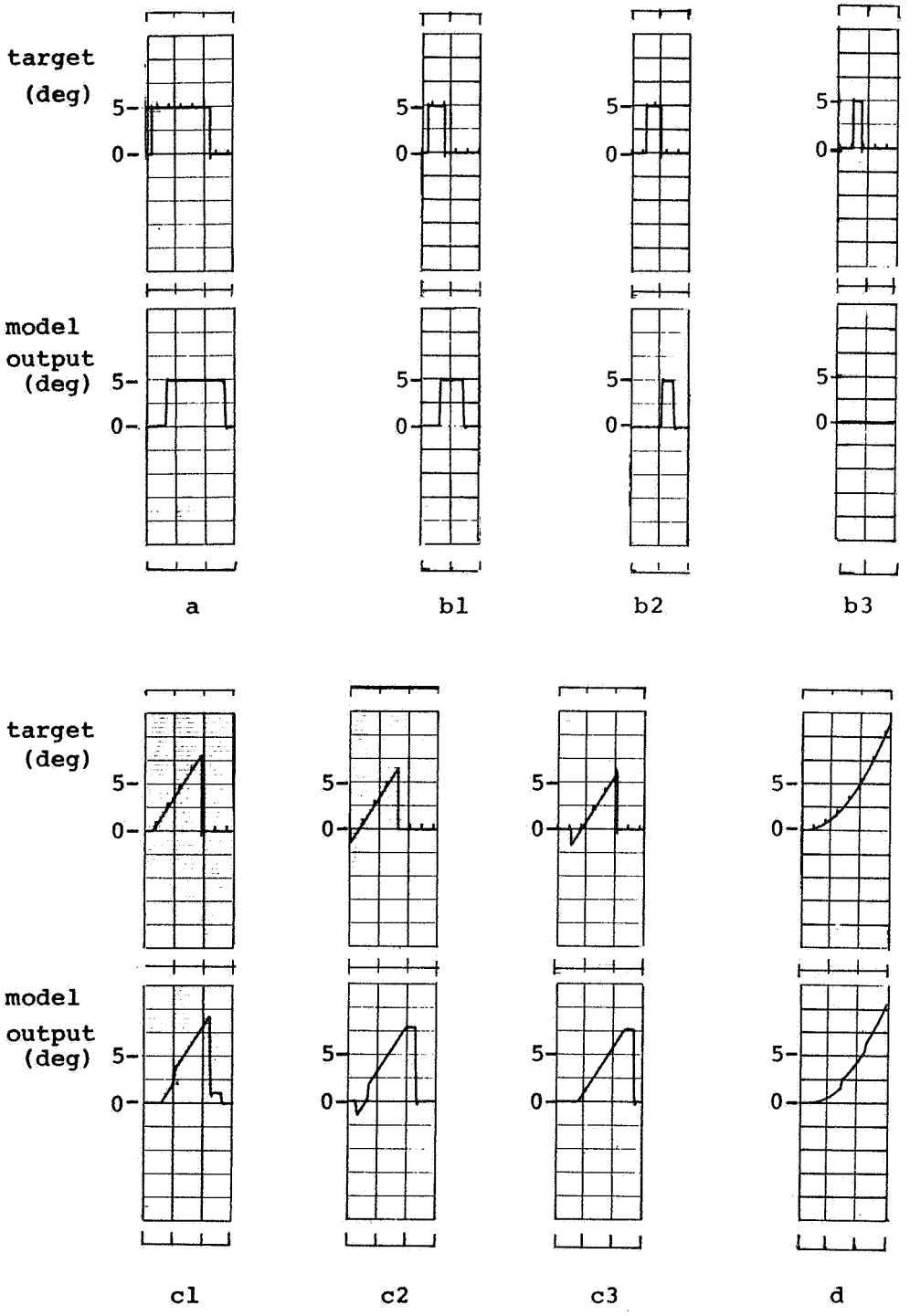


Figure 4.—Model responses to various target inputs: (a) step (5 deg), (b) pulse (5 deg).

(2) As can be seen from figure 4(c), the model predicts different responses to the same type of input. This depends on the synchronization of the first sample with the input. A look at a series of outputs, with varying synchronization, shows the different responses that the model predicts. Figure 4 is a series of responses to a single 10 deg/sec ramp input. The sampling interval of 0.2 second is divided into 10. The first sample is synchronized to the input for the leftmost case, and occurs delayed by an additional 0.02 second for each following case, with the eleventh case a repeat of the first one. There is twice a double saccadic correction, and only once an offset error during the ramp. This variety of response types to a 10 deg/sec ramp agrees with the measured response frequencies presented by Robinson (ref. 2) in his detailed study of pursuit dynamics. For comparison his data is shown in figure 2. At the end of the input in figure 5, we see the probability of having the sawtooth appearance.

Figure 6 shows the series of responses to the step-ramp. Synchronization between first sample and input varies as in figure 5. The successive cases show a variety of saccadic response corrections to this step-ramp input. When the returning target has not moved sufficiently far back toward the origin at the sampling instant, a second saccadic correction in the direction of the ramp is elicited.

Thus, as seen from figures 4(c3), 4(c2), and 6, the model predicts variously none, one, or two saccadic corrections to the same step-ramp input. All first saccades appear within a time interval, which is the sum of τ and T_1. These responses are in accord with the various pursuit-saccadic categories observed in following a step-ramp by Rashbass (ref. 4) and Robinson (ref. 2). A detailed analysis of the model responses to this case is given in the appendix.

FREQUENCY RESPONSE

A study of the frequency response shows that the model has two modes of tracking. Figure 7 shows the model response to 5 degree input sinusoids at three different frequencies. At low frequencies the model follows the input closely, and saccadic corrections appear at maximum deviation of the target. With increasing frequency, more saccades occur, the output amplitude goes up, and there is an increase in phase lag. It should be emphasized that this is not the predicted eye movement response to a single sinusoid, which involves a predictive mode of tracking. The model frequency response plot, based on single sinusoid analysis, is shown in figure 8. The maximum of the amplitude ratio as well as the phase varies with input amplitude because of the system nonlinearities.

Figure 9 shows the frequency response of the nonpredictive eye-movement system as measured by several investigators (nonpredictive tracking). Although the phase relationships of the model agree well with the experimental, considerable discrepancy is apparent in the amplitude ratio at low frequencies.

SACCADE-SYNCHRONIZED EXPERIMENTS

As seen in the transient response analysis, the synchronization of input to sampling instants is the single most important factor in determining the response of the revised sampled data model for eye tracking movements. Since there is no output at the instant of a sample, the only way to estimate when a sample occurred is by observation of a saccade resulting from a sample. The model predicts that a sample occurred exactly T_1 seconds before every saccade. If an input occurs immediately after a saccade, the sample that caused that saccade and the sample that will cause a response to that input will be separated by only one intersample time. Therefore, if eye movements are controlled by a system such as the revised sampled data model, the distribution of intersample times will be

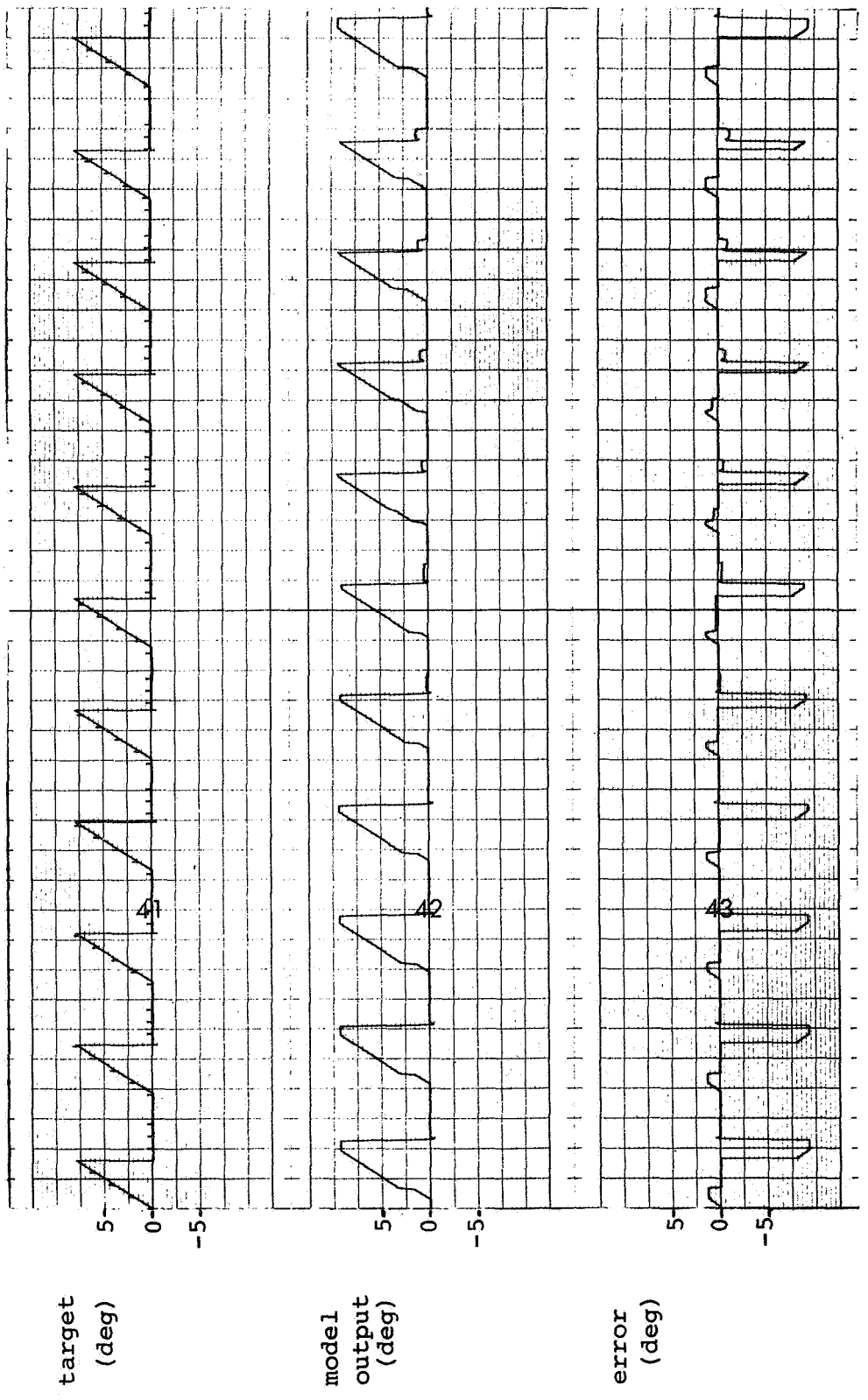


Figure 5.—Series of model responses to a ramp input (10 deg/sec) with synchronization between input and first sample varying from 0.0 to 1.0 τ in steps of 0.1 τ. Plot shows input, output, and error. The time scale is superimposed on the input (time between pulses is τ=200 msec).

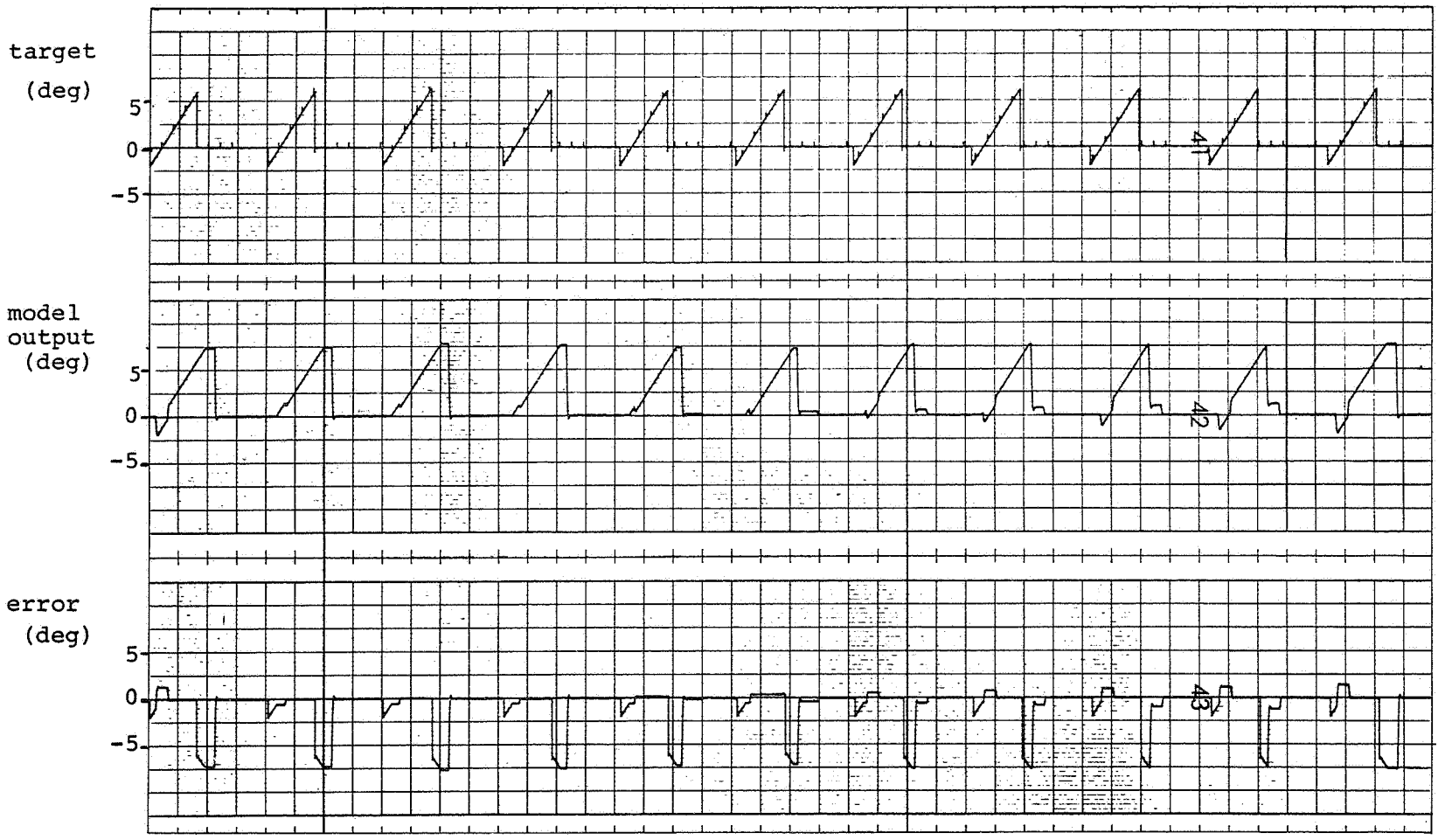


Figure 6.—Series of model responses to a step-ramp input (-2 deg, 10 deg/sec) with synchronization between input and first sample varying from 0.0 to 1.0 τ in steps of 0.1 τ. Plot shows input, output and error. The time scale is superimposed on the input (time between pulses is τ=200 msec).

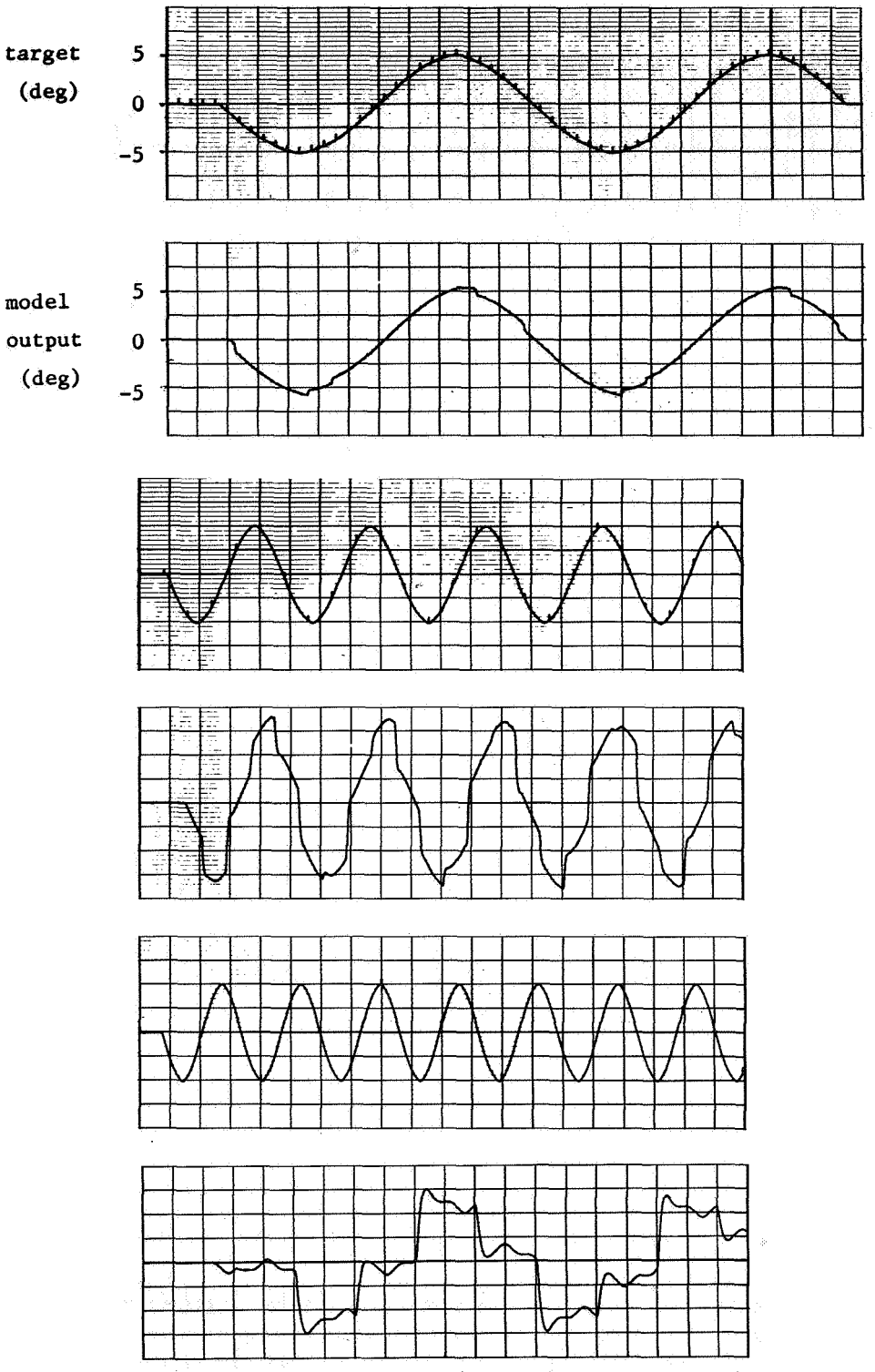


Figure 7.—Model response to a single sinusoid (nonpredictive tracking) for three frequencies: f=0.194 hertz (top left), f=1.04 hertz (top right), and f=3.82 hertz (bottom). The time scale is superimposed on the input (time between pulses is 200 msec).

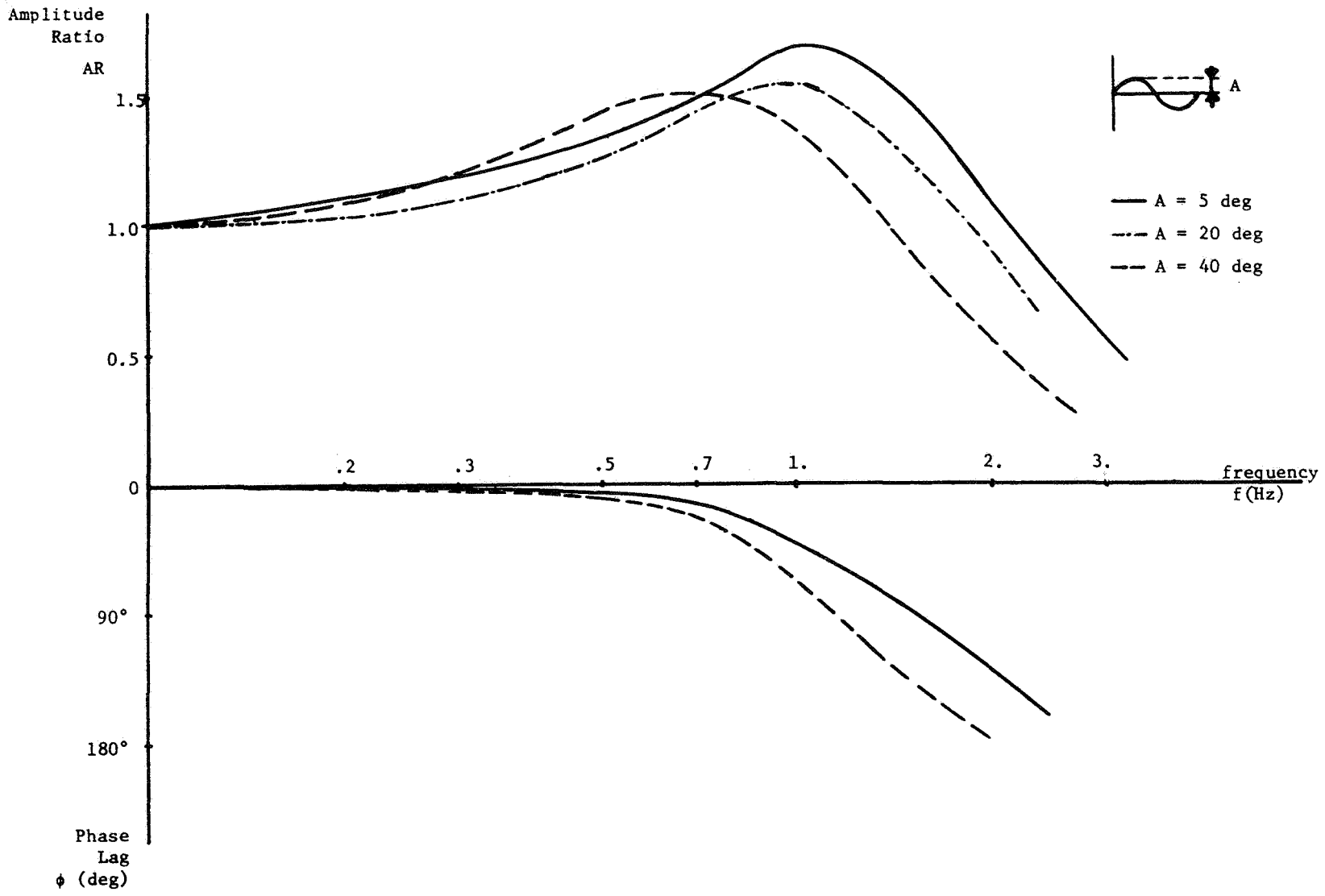


Figure 8.—Frequency response plot of the model for various input amplitudes.

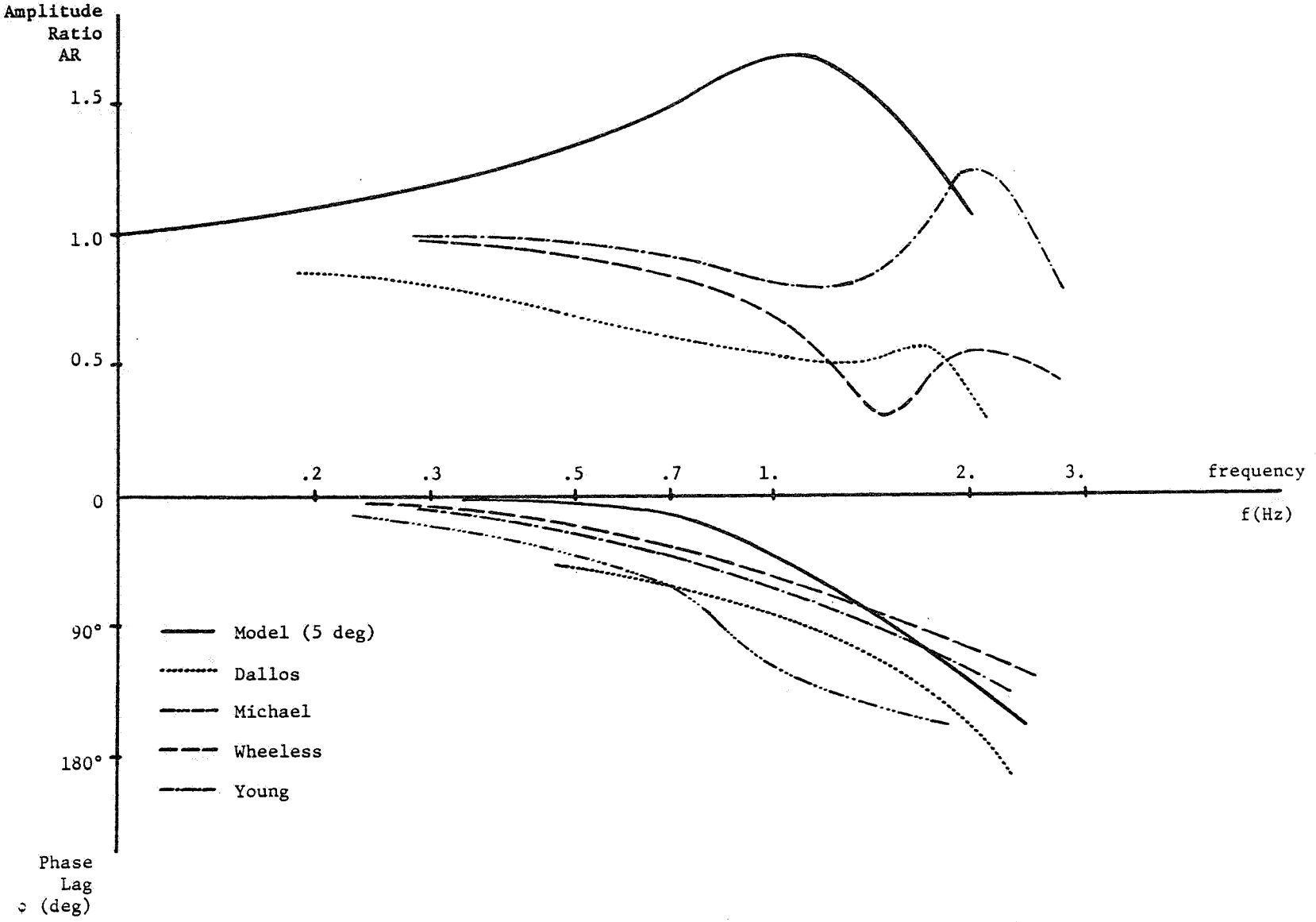


Figure 9.—Frequency response of eye tracking movements (nonpredictive mode) established by several investigators and compared with model responses.

revealed by the distribution of responses to an input that always occurs at the same constant time after a saccade. Further, the sampler control logic of a sampled data model will be revealed by the changes in response distributions as the constant time after a saccade changes.

In a sampled data system with target-synchronized sampler control logic, the average latency to a step will not change as a function of time after the last saccade because each target movement triggers its own sample. If the system also has a minimum time of 200 msec between samples, then for steps introduced a short time after saccades the system must wait for this minimum time to elapse before allowing another stochastic delay preceding a sample. For this sampler control logic, then, as time delay from the last saccade to a step increases from zero, average latency should decrease linearly with slope -1 from an initial high value until the minimum intersample time requirement no longer constrains the system. As delay from saccade to step continues to increase, this system would show no change in latency.

In a sampled data system with nonsynchronized sampling, the distribution of intersample times determines exact latency characteristics. As the time from saccade to step increases from zero to the first expected occurrence of the next sample, average latency should decrease as less and less time elapses from the input to the next sample. As the time from saccade to step increases through the neighborhood of the next sample, average latency increases as a greater percentage of inputs must wait for the second sample to cause a response. As the time from saccade to step further increases above the expected occurrence of the first sample, latency again decreases as all inputs must wait for the second sample and the time from input to next sample is decreasing as it was for small delays. Thus a nonsynchronized sampled data system predicts decreasing, then increasing, and then decreasing again latency trends as time from saccade to step increases.

Four such saccade-synchronized experiments were performed at the MIT man-vehicle laboratory. Experiment 1 was a returning pulse in which the return of the target was synchronized to the occurrence of a saccade in response to the initial step. Experiment 2 was a continuing pulse in which the second outward step was synchronized to the occurrence of a saccade in response to the initial step (see fig. 10). Experiment 3 was a ramp with inward step in which the occurrence of the inward step was synchronized to the occurrence of a saccade in response to the initial ramp. Experiment 4 was a ramp with outward step in which the occurrence of the outward step was synchronized to the occurrence of a saccade in response to the initial ramp. These experimental inputs were mixed at random and presented to six subjects. For a complete description see Forster (ref. 21).

Figure 6 shows latencies, in response to the synchronized step of the first two experiments, plotted as a function of time after the last saccade. Plotted on the same graph are the predictions of the revised sampled data model with target synchronized sampler control logic (τ_{min}=200 msec, T_1=100 msec, L_{ave}=250 msec) and with nonsynchronized sampler control logic with samples uniformly distributed between 150 and 250 msec. The results of experiments 3 and 4 were inconclusive, showing no meaningful variation of latency as a function of time after a saccade.

The longer latencies of the returning pulse, compared with the continuing pulse, are in agreement with the results of Beeler and are probably due to muscle hysteresis nonlinearities and viscoelastic elements in the eye. The fact that each response is modeled by a different sampler control logic suggests a system with nonsynchronized sampling in which the eye can adjust the sampling slightly in phase and frequency according to observed target movements. This system can model both the increasing portion of latency distributions by shortening the sampling interval and Wheeless's pulse-step results by lengthening the sampling interval.

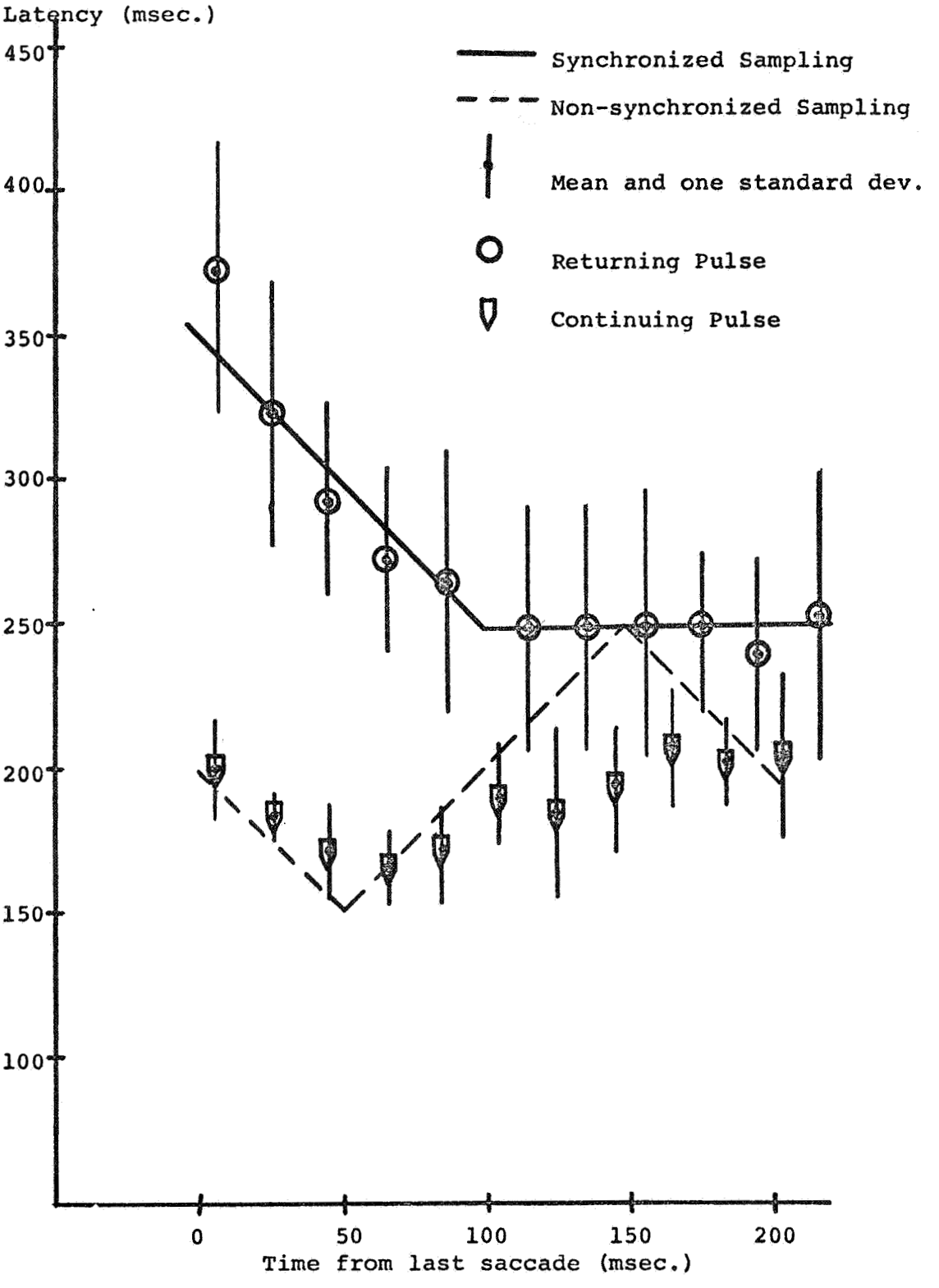


Figure 10.—Results of two saccade-synchronized experiments.

DISCUSSION

Responses of the revised sampled data model have been shown to agree with observed classes of eye movement including steps, pulses, ramps, and step-ramps. In particular, the percent of forms of responses observed in actual eye movements to identical stimuli has been shown to agree with percents predicted by uniformly varying the synchronization of input to sampling instants in the revised sampled data model. The frequency response has been shown to be nearly that of the eye movement control system. The revised model agrees with the findings of Rashbass (ref. 4) that the pursuit eye movement control system is independent of the saccadic control system and proportional to target rate only. The system also agrees with Robinson's findings that the pursuit eye movement control system is continuous. Further, the revised model does not predict pursuit movement in response to small steps as the original model did.

Saccadic inaccuracy and variation in pursuit movement may be modeled by considering the slopes of the nonlinearities stochastically variable. A slope greater than one would produce overshoot, and a slope less than one would produce undershoot. This variability could explain the pursuit velocity exceeding the target velocity in some of the responses observed by Robinson. Further study of these characteristics is necessary to describe the stochastic processes involved.

The revised sampled data model also includes some predictive effects as seen in the agreement of the two sampler control logics with the results of Zuber. The eye shows much more predictive ability than this, however, as seen in the eye's ability to suppress a saccade and increase pursuit latency in various step-ramp experiments. The revised sampled data model predicts this pure pursuit response in a region of step-ramps very close to the region of observed pursuit-only response (ref. 21). This prediction, however, requires that no sample occur in approximately the first 134 msec after the onset of target motion, an event that has a low probability. The model also does not predict the observed longer pursuit latency. Since many no-saccade responses are observed, there is probably a predictive function involved even in nonpredictive tracking.

Although transient responses are well modeled by uniform variation in synchronization of input to sampling instants, synchronization does not explain some other characteristics of eye movement. For example, a nonsynchronized sampled data model cannot predict increasing frequency distributions for step latency. The saccade-synchronized experiments show that it is necessary to change sampler control logic depending upon the input to model the effects of muscle dynamics on latencies to steps immediately following saccades. Further study in saccade-synchronized experiments should include longer times from saccade to input and a step-step-ramp experiment in which the step-ramp is saccade-synchronized.

Impulsive sampling also does not model the pulse-step results of Wheeless, but an extension to finite width sampling is compatible with Wheeless's results. If, for example, a finite width sample occurred during the target step from plus to minus, the sampled error would contain both positive and negative parts that could cancel each other and thus delay the saccadic response until after the next sample. If the pulse width were 40 msec and the average intersample time 200 msec, about 20 percent of samples would cross the plus to minus step (as described above), causing an overall increase in average response time of 40 msec, in good agreement with Wheeless's results.

Subject to the limitations and extensions discussed, the revised sampled data model has been shown to predict responses resembling eye tracking movements with remarkable accuracy. It therefore is a useful tool in predicting eye movement response based on target movement only.

APPENDIX

To evaluate the probability of having none, one, or two saccadic corrections, we can make use of figure 11, which is a composite picture of the step-ramp error signal, as seen in figures 5 and 6. We now assume that the input may start at any time between sample

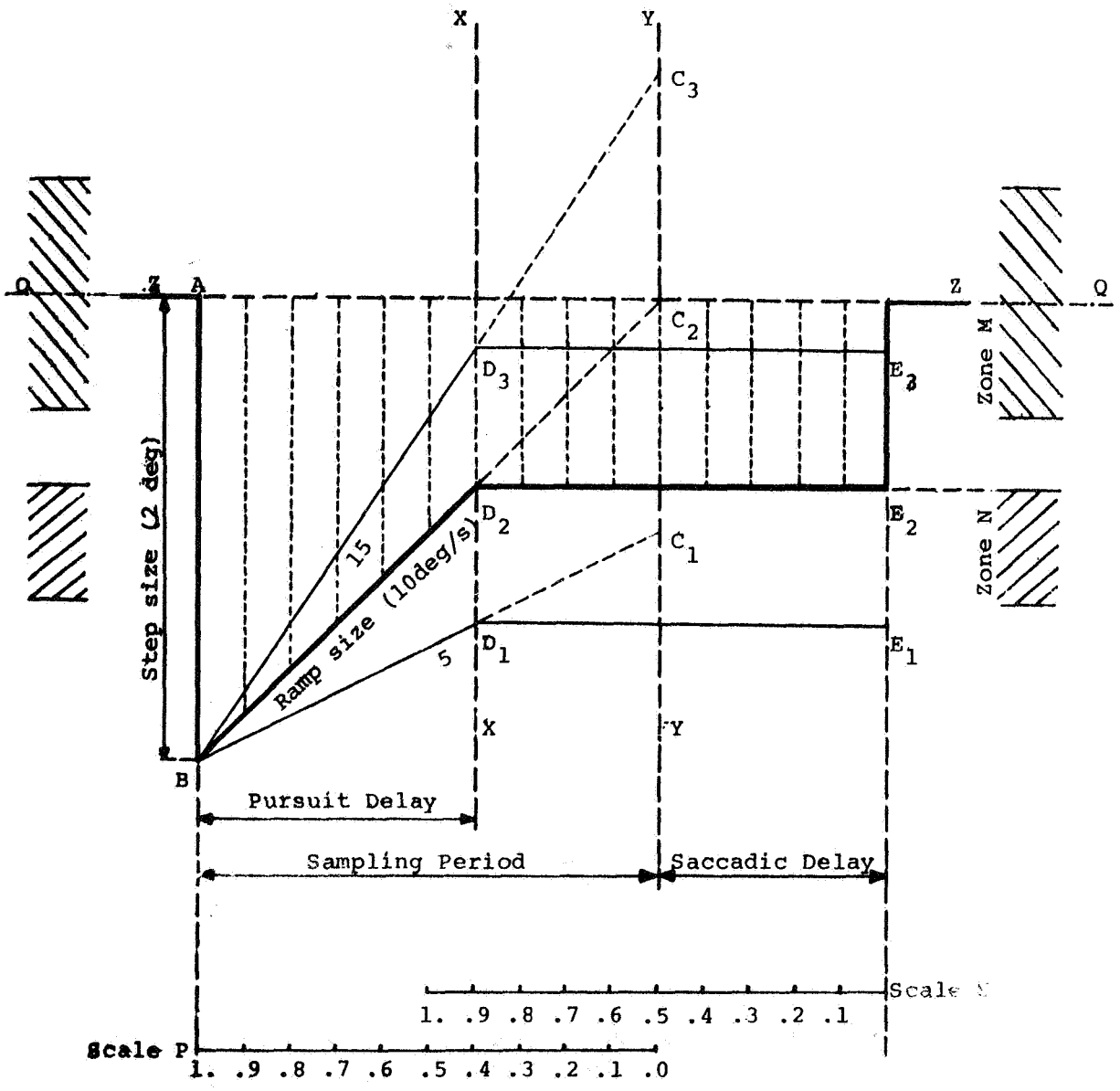


Figure 11.—Diagram of the step-ramp error signal with entry for synchronization between input and first sample on scale S and entry for saccade jump size on scale P. Parameters are sampling period (τ = 200 msec), saccadic delay (T_1=100 msec), pursuit delay (T_2=120 msec), step size (2 deg), ramp size (D_2E_2=10 deg/sec) and dead zone threshold (0.5 deg). The values in the example are those in parentheses.

instants, and we divide this interval again in 10. (The parameters used in this sketch are slightly different from the ones mentioned earlier, for simplicity of presentation.) If the sample occurred just before A, there is an initial error AB, which decreases according to BC_i (slope varying with the ramp size). After the pursuit delay time (line XX) the error remains constant (line D_iE_i). At the next sample the error is sensed, and if it exceeds threshold, it is reduced to zero, following a saccadic delay. (Jump from line D_iE_i to reference line ZZ, if D_iE_i is out of zone M.) For a larger input synchronization delay, the error duration becomes shorter (as seen in figs. 5 and 6). If the sample then occurs at a time prior to the pursuit delay, the saccadic jump will overcorrect the error. The size of the jump is read on the scale P, and is applied at a moment read on the scale S. If the correction brings forth an offset in position larger than the dead zone characteristics, a second saccadic correction will appear. (The moment at which a second saccade will show up is read from the sketch at the crossing of the line BD_i and the zone N, the latter being fixed to the line D_iE_i.) For example, if the latency between input and a sample is 0.7, the first saccade will occur at 0.7 on the scale S, and the size of the jump is read at 0.7 on the scale P. Since the size of the saccade is so large that it falls outside the zone N (step of -2 degrees, ramp of 10 deg/sec), a second corrective saccade at the next sample is required to bring the error to zero (compare with fig. 6).

With this figure, one can analyze the chances of having none, one, or two saccades, and one can evaluate their probability, under the assumption of uniformly distributed sampling, for any combination of step-ramp inputs. The diagram has saccadic delay T_1, pursuit delay T_2, ramp size, and step size as parameters. For the latter, one shifts zone M and reference line QQ up or down. The zone N is fixed to the line D_iE_i, resulting from the ramp size and the pursuit delay. Being in the zone M means no saccade at all. Being in the zone N means only one saccade, and outside this zone N means two saccades. Their magnitude is read at the entry on the scale P, and applied at the entry on the scale S.

REFERENCES

1. Beeler, G. W.: Stochastic Processes in the Human Eye Movement Control System. Ph.D. thesis, California Institute of Technology, May 1965.
2. Robinson, D. A.: The Mechanics of Human Smooth Pursuit Eye Movement. J. Physiol., vol. 180, 1965, pp. 569-591.
3. Young, L. R.: A Sampled Data Model for Eye Tracking Movements. Dept. of Aeronautics and Astronautics, MIT, June 1962.
4. Rashbass, C.: The Relationship Between Saccadic and Smooth Tracking Eye Movements. J. Physiol., vol. 159, 1961, p. 326.
5. Vossius, G.: Der Kybernetishe Aspekt der Willkurbewegung. Progress in Biocybernetics (Japan), vol. 2, 1965, pp. 111-140.
6. Zuber, B. L.: Physiological Control of Eye Movement in Humans. Ph.D. thesis, Dept. of Nutrition and Food Science, MIT, June 1965.
7. Wheeless, L. L.: The Effects of Intensity on the Eye Movement Control System. Ph.D. thesis, Univ. of Rochester, 1965.
8. Jury, E. I.; and Pavlidis, T.: Discussion of a Sampled Data Model for Eye Tracking Movements. Second International Congress of the International Federation of Automatic Control (Basel, Switzerland), Butterworths, Ltd., Aug. 1963, p. 461.
9. Johnson, L. E.: Human Eye Tracking of Aperiodic Target Functions. Systems Research Center, #37-B-63-8, Case Institute of Technology.
10. Meiry, J. L.: The Vestibular System and Human Dynamic Space Orientation. Sc.D. thesis, MIT, Dept. of Aeronautics and Astronautics, June 1965.

11. Sugie, N.: The Mechanism of Eye Movements. Bull. Electrotech. Lab. (Japan), vol. 30, no. 7, July 1966.
12. Dallos, P. J.; and Jones, R. W.: Learning Behavior of the Eye Fixation Control System. IEEE Transactions on Automatic Control, vol. AC-8, no. 3, July 1963.
13. Michael, J. A.: An Analysis of a Predictive Component in the Human Visual Tracking System. M.S. thesis, McGill University, Apr. 1964.
14. Lässig, P.: Critical Observations on the Study of the Eye-Following System with Unpredictable Movements of the Aiming Object. (Ger.) Acta. Biol. Med. Ger., vol. 14, 1965, pp. 618-29.
15. Milhorn, H. T.: The Application of Control Theory to Physiological Systems. W. B. Saunders & Co., 1966.
16. Milsum, J. H.: Biological Control Systems Analysis. McGraw-Hill Book Co., Inc., 1966.
17. Jones, G. M.; and Milsum, J. H.: Spatial and Dynamic Aspects of Visual Fixation. IEEE Transactions of Bio-Medical Engineering, vol BME-12, no. 2, Apr. 1965, pp. 54-62.
18. Fuchs, A. F.: Saccadic and Smooth Pursuit Eye Movements in the Monkey. J. Physiol., vol. 91, 1967, pp. 609-631.
19. Saslow, M. G.: Latency for Saccadic Eye Movements. J.O.S.A., vol. 57, no. 8, Aug. 1967, pp. 1029-1033.
20. Westheimer, G.: Eye Movement Response to a Horizontally Moving Visual Stimulus. A.M.A. Arch. Opthal., 1954, pp. 932-943.
21. Forster, J. D.: A Stochastic Revised Sampled Data Model for Eye Tracking Movements. S.M. thesis, MIT, Dept. of Aeronautics and Astronautics, June 1968.